GRAVITY BOILING STUDIES

(Final report to the NASA Lewis Research Center
on research done under the first one-year
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by

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CIRCUMSTANCES AND OBJECTIVES

The present report accounts for progress under NASA Grant NGR-18-001-035, "Interacting Effects of Gravity and Size Upon the Peak and Minimum Pool Boiling Heat Fluxes", during its first extension following an original two-year grant. The extension period was from September 1, 1969 to December 31, 1970.

The primary objectives of the project were three fold:

1.) The work of the first two years revealed that the hydrodynamic mechanisms of the peak and minimum heat fluxes fail when the Bond (or Laplace) number becomes small. An objective of the extension grant was to learn what mechanisms dictate boiling heat fluxes in the near-zero-gravity range, and to develop predictive equations. This was to be done for the specific case of small cylindrical heaters.

2.) A second matter of some importance that arose during the original grant period had to do with the role of viscosity in boiling. We showed that heaters could induce side-flows through viscous action, and that these flows could in turn increase the peak heat flux significantly. We therefore set out in the extension period to determine whether there might be significant direct effects of viscosity on the extreme boiling heat flux.

This question was to be attacked from two directions: First, a flat plate heater was to be built with vertical side walls to prevent the secondary viscous effect of induced convection from entering the experiment. This heater was to be effectively increased

in size relative to the Taylor unstable wavelength by operating it in the centrifuge facility. This test was to provide a determination of the influence of viscosity on the peak heat flux on an infinite flat plate, for comparison with the existing inviscid hydrodynamic theory for flat plates.

The second line of attack was theoretical. We proposed to include viscosity in the conventional stability theory, and then to include the viscosity-modified unstable wavelengths in the hydrodynamic formulation of the peak and minimum heat fluxes. This was to provide a quantitative indication of how much direct influence of viscosity we might expect in experiments.

3.) The third major objective was that of establishing the analogy between boiling and electrolysis. Since these processes have much in common we proposed to delineate the analogy between them so that information relating to one process might be used to explain the other. This was to be done first for the individual bubble growth problem and then for the gross process.

This work was done under the cognizance of the NASA Lewis Research Center with Mr. Thomas H. Cochran acting as Project Manager. The electrolysis analogy work was done in cooperation with a Themis Project entitled "Bubble Dynamics" within Grant DAA B07-69-C-0366 under the direction of Prof. James E. Funk.

PROGRESS

A.) Carryover: The Appendix lists three papers describing work done during the first two years, which were completed and appeared in print during the extension period. They are Appendix

items 1.), 2.) and 3.).

1.) J. H. Lienhard and K. H. Sun, "Effects of Gravity and Size upon Film Boiling from Horizontal Cylinders," Jour. of Heat Transfer, vol. 92, No. 2, 1970, p. 292.

2.) J. H. Lienhard and K. B. Keeling, "An Induced Convection Effect upon the Peak Heat Flux," Jour. Heat Transfer, vol. 92, No. 1, 1970, p. 1.

3.) K. H. Sun and J. H. Lienhard, "The Peak Pool Boiling Heat Flux on Horizontal Cylinders," Int. Jour. Heat, Mass Transfer, vol. 13, 1970, pp. 1425-1439.

B.) The range of small Bond number: An experimental determination of the heat vs.temperature difference curve for very small wires revealed that the peak and minimum heat fluxes no longer occur. A description of this behavior, along with a quantitative explanation of it are the subject of a report which we list as Appendix item 4.):

4.) N. Bakhru and J. H. Lienhard, "On the Non-Existence of Peak and Minimum Boiling Heat Fluxes at Low Gravity," University of Kentucky, TR No. 18-70-ME 5, March, 1970.

Subsequent work has been aimed toward expanding our capability for predicting the heat flux as a function of temperature difference over the full range of the curve. This involved the development of heat transfer predictions: for convection in the very small Nusselt number range; for the mixed film-boiling and convection mode that was peculiar to this configruation; and for film boiling on very small wires. Additional experiments were also made to show how this transition of behavior evolves with decreasing wire size (or decreasing gravity).

This work will be the subject of a Ph.D. thesis which should be completed in the summer of 1971.

C.) Peak heat flux on infinite flat plates and the role of viscosity:

Theoretical: The first stage in this effort was to prepare a detailed review of the inviscid hydrodynamic theory of boiling and some of its background. This was the subject of a report which we list as Appendix item 5.):

5.) V. Dhir, "Some Notes on the Development of the Hydrodynamic Theory of Boiling", University of Kentucky, TR No. 19-70-ME-6, March 1970.

The next step was to include viscosity in the prediction of the Taylor unstable wavelength. This has been completed and predictions of the dimensionless wave frequency as a function of a dimensionless wavelength have been computed numerically with the Borishanski number as a parameter. The prediction applies to both flat plates and cylinders.

Application of this wavelength information has been made to the prediction of the minimum heat flux, and additional work is presently being done toward applying it to the prediction of the peak heat flux. These efforts are to be the subject of a Ph.D. thesis which is scheduled for completion in the early Fall of 1971.

Experimental: We have measured the Taylor unstable wavelength during film boiling in viscous liquids (cool glycol and isopropanol) and obtained partial verification of the viscous theory. This line of experimentation is about half finished.

A flat plate apparatus was completed and shake-down testing on it has been started. This apparatus posed a particularly knotty design problem which led us into some peripheral work described below. The flat plate experiments and the Taylor wavelength experiments are to be part of the Ph.D. thesis presently under completion.

Some related work: The design of the flat plate apparatus gave rise to the problem of designing a reflux condenser in the spatially varying gravity field of the centrifuge apparatus. In resolving this problem we saw how to solve three related problems of condensation and natural convection in varying gravity fields. At the cost of modicum of time from one Research Assistant we wrote three papers which are listed as Appendix items 6.), 7.), and 8.):

6.) V. Dhir and J. H. Lienhard, "Laminar Film Condensation on Plane and Axi-Symmetric Bodies in Non-Uniform Gravity," Jour. Heat Transfer, vol. 93, No. 1, 1971, pp. 97-100.

7.) J. H. Lienhard, R. Eichhorn, V. Dhir, "Laminar Natural Convection Under Non-Uniform Gravity," under review.

8.) J. H. Lienhard and V. Dhir, "A Simple Analysis of Laminar Film Condensation with Suction," under review.

D.) The boiling-electrolysis analogy: This work was begun with a nondimensionalization of existing buble growth theories. It was then possible to compare an electrolysis bubble growth theory with bubble growth data and, in so doing, to extend our predictive capability. This development was first presented in Appendix item 9.).

9.) A. Bhattacharya and J. H. Lienhard, "The Similarity of Bubble Growth in Boiling and Electrolysis," University of Kentucky, TR 23-70-ME-7, May, 1970.

and then streamlined and extended a little, and submitted for publication in the form of Appendix item 10.):

10.) A. Bhattacharya and J. H. Lienhard, "Similarity of Vapor and Gas Bubble Growth," under review.

The second phase of this work began with the development of current vs. applied voltage curves for horizontal wires. These

curves exhibited a peak similar to that shown by the boiling curve. Close scrutiny showed that this transition occurred not at the point at which escaping gas jets became Helmholtz unstable, but rather at the point where such jets first form. The transition from the region of isolated bubbles to the region of jets and columns is known in boiling and is predictable for the flat plate geometry.

A master's thesis scheduled for completion in the early summer will report all of this work. It will conclude the description of the electrolysis transition a.) by showing why the electrolysis curve peaks at the first transition instead of the second; b.) by deriving a prediction of the first transition point for cylindrical geometry; and c.) by adapting this prediction to the electrolysis process, and rationalizing both boiling and electrolysis data with it.

E.) Some additional items: A major in-project service effort, developed in conjunction with the other work, was a large computer program which contains thermal properties of the fluids we have been using, and will present our experimental data in any scheme of correlation we might arbitrarily choose. This program has been immensely helpful and we have written it up in the form of a report which we present as Appendix item 11.):

11.) R. A. Reich and J. H. Lienhard, "A Computer Program for Correlating Peak and Minimum Heat Fluxes," University of Kentucky report in press.

During the Grant period, another research effort has been supported to the extent of expendable supplies and project expertise. This is a study of the peak heat flux on spheres. It will

be reported in a master's thesis to be completed this summer. The thesis will present a successful hydrodynamic theory of the peak heat flux supported by original measurements.

A final spinoff item is listed as Appendix item 12.):

12.) J. H. Lienhard and J. E. Funk, "Deisgn of a Perfectly 'Effective Boiling Fin," Jour. of Basic Eng., in press.

This was a brief note relating to the design of boiling fins.

APPENDIX

Papers and Reports from Grant Period: 9/1/69 to 12/31/70

1.) J. H. Lienhard and K. H. Sun, "Effects of Gravity and Size upon Film Boiling from Horizontal Cylinders," Jour. of Heat Transfer, vol. 92, No. 2, 1970, p. 292.

2.) J. H. Lienhard and K. B. Keeling, "An Induced Convection Effect upon the Peak Heat Flux," Jour. Heat Transfer, vol. 92, No. 1, 1970, p. 1.

3.) K. H. Sun and J. H. Lienhard, "The Peak Pool Boiling Heat Flux on Horizontal Cylinders," Int. Jour. Heat, Mass Transfer, vol. 13, 1970, pp. 1425-1439.

4.) N. Bakhru and J. H. Lienhard, "On the Non-Existence of Peak and Minimum Boiling Heat Fluxes at Low Gravity," University of Kentucky, TR No. 18-70-ME-5, March, 1970.

5.) V. Dhir, "Some Notes on the Development of the Hydrodynamic Theory of Boiling," University of Kentucky, TR No. 19-70-ME-6, March 1970.

6.) V. Dhir and J. H. Lienhard, "Laminar Film Condensation on Plane and Axi-Symmetric Bodies in Non-Uniform Gravity," Jour. Heat Transfer, vol. 93, No. 1, 1971, pp. 97-100.

7.) J. H. Lienhard, R. Eichhorn, V. Dhir, "Laminar Natural Convection Under Non-Uniform Gravity," under review.

8.) J. H. Lienhard and V. Dhir, "A Simple Analysis of Laminar Film Condensation with Suction," under review.

9.) A. Bhattacharya and J. H. Lienhard, "The Similarity of Bubble Growth in Boiling and Electrolysis," University of Kentucky, TR 23-70-ME-7, May, 1970.

10.) A. Bhattacharya and J. H. Lienhard, "Similarity of Vapor and Gas Bubble Growth," under review.

11.) R. A. Reich and J. H. Lienhard, "A Computer Program for Correlating Peak and Minimum Heat Fluxes," University of Kentucky report in press.

12.) J. H. Lienhard and J. E. Funk, "Deisgn of a Perfectly 'Effective Boiling Fin," Jour. of Basic Eng., in press.